DECODING INDIA'S GREEN HYDROGEN POTENTIAL

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SUMMARY

India's position in the global green hydrogen market is complex, marked by both challenges and opportunities. Currently, green hydrogen production costs in India are estimated between \$5.30 to \$6.70 per kilogram (kg), approximately 40 percent more expensive than the cheapest G20 green hydrogen producer, Australia. To compete as a hydrogen exporter, India must reduce its production costs by around 30 – 40 percent. Furthermore, a domestic transition from traditional natural-gas derived (grey) hydrogen to renewable energy-derived (green) hydrogen will incur a substantial green premium, approximately 2 – 3.5 times current grey hydrogen prices. The bulk of green hydrogen production costs, nearly 95 percent, are driven by capital costs, like equipment to produce hydrogen and renewable energy, and the cost of capital. Thus, investment and policy initiatives targeted towards achieving green hydrogen cost parity should focus on these elements. India's large fertilizer and refinery industries represent a pathway to reduce capital costs by offering a tangible demand baseline, an element that, when missing, could significantly increase the cost of capital. This demand baseline represents a significant advantage, as only 10 percent of planned green hydrogen production by 2030 have secured off-takers.[1] *As currently constructed, India may need more than the \$2.1 billion it has already committed to make green hydrogen a viable component of its energy strategy.*

1. INTRODUCTION

India is undertaking a rapid clean energy transition. With a promise to reach net-zero emissions by 2070, India must decarbonize an array of sectors including transportation, heavy industry, and electricity generation. Traditional renewable energy sources like wind and solar are instrumental in tackling many of these challenges. India has already installed 180 gigawatts (GW) of renewable energy capacity and aims to achieve 500 GW by 2030.[2] However, hard-to-abate industries such as fertilizer production, refineries, steel manufacturing, and chemical production remain difficult to decarbonize and are crucial to not only meeting the country's economic aspirations, but also as a source of new future emissions.[3]

The element hydrogen could aid in decarbonizing these sectors, but 96 percent of the world's hydrogen is generated through emissions-intensive processes due to lower costs than emissions-free production. As global decarbonization efforts grow, many countries, including India, are looking to reduce costs of cleaner, emission-free hydrogen ("clean hydrogen"). These efforts not only seek to use the element in an energy transition, but also as an economic opportunity, by capitalizing on the emerging hydrogen value chain that may transform its use from predominately local to regional and global.[4]

Yet, India's role in the future global hydrogen economy is uncertain. The nascent hydrogen value chain is complex, and countries are determining how they will integrate within this growing market. Among the largest economies in the world, the G20, most

[1] "Hydrogen offtake is tiny but growing," *BNEF,* November 14, 2023, https://about.bnef.com/blog/hydrogen-offtake-is-tiny-but-growing/#:~:text=Many%20companies%20have%20plans%20to,for%20clean%20hydrogen%20and%20derivatives.
[2] Saurabh Handa, "India Clean Energy: Progress and Policy," Citi Group, October 31, 2023, https://www.citigroup.com/global/insights/global-insights/india-clean-energy-progress-policy.
[3] Simon Bennett, "India Energy Outlook 2021," IEA, February 2021, https://www.iea.org/reports/india-energy-outlook-2021.
[4] Timur Gül et al., "Global Hydrogen Review 2023," IEA, September 2023, https://www.iea.org/reports/global-hydrogen-review-2023.

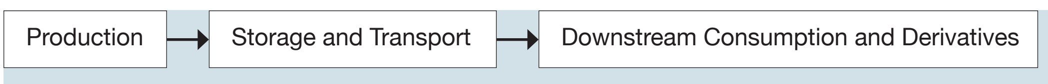
countries have stated intentions to become net exporters of hydrogen (see Table 2).

In the case of India, and many other stated exporters, the feasibility of these hydrogen export goals are unclear. Some previous analyses classify India as a clear (future) importer or bystander of clean hydrogen and many of its derivatives (such as ammonia or methanol) while others conclude that India is posed to be a medium to large exporter in future hydrogen markets.[5][6][7][8]

This analysis aims to build on this discussion by precisely quantifying India's position within the global hydrogen landscape through clean hydrogen production costs. The opening section defines the hydrogen value chain at-large and various hydrogen production methods. Next, the following section describes the current state of this value chain globally and domestically in India and then defines a modeling framework to estimate current and future production costs of clean hydrogen and their drivers within India with relevant comparisons traditional hydrogen production methods. Subsequently, the analysis contextualizes India's clean hydrogen production costs to the G20 at-large. The author then offers conclusions and recommendations to those looking to understand what role India will play in the future of global hydrogen.

2. DEFINING CLEAN HYDROGEN AND THE HYDROGEN VALUE CHAIN

Figure 1: The Green Hydrogen Value Chain



Source: Author adaptation from McKinsey analysis.[9]

The hydrogen value chain consists of three interconnected components: production, storage and transportation, and downstream use cases.[10] After production, hydrogen can be stored in both liquid and gaseous states, or as chemical derivatives like ammonia. Pipelines, liquid hydrogen, and ammonia shipping are the primary transportation methods. Significant uncertainty exists within this stage specifically concerning the safety, cost, and accessibility of these storage and transport methods. While there are several hydrogen pipelines integrated globally, hydrogen shipping is largely untested, with the world's first liquified hydrogen carrier being built in 2020 and the first test shipment occurring in February 2022.[11] To date, no other carrier has been built or operationalized. Finally, in downstream use cases, hydrogen and its derivatives are the

[5] Gül et al., "Global Hydrogen Review 2023."
[6] Laima Eicke and Nicola De Blasio, "The Future of Green Hydrogen Value Chains," Belfer Center, October 2022, https://www.belfercenter.org/sites/default/files/files/publication/Paper_MappingHydrogen_Final.pdf.
[7] Lucie Togni and Rami Fakhoury, "Regional Insights into Low-Carbon Hydrogen Scale Up," World Energy Council, April 2022, https://www.worldenergy.org/publications/entry/regional-insights-low-carbon-hydrogen-scale-up-world-energy-council.
[8] Herib Blanco and Emanuele Taibi, "Global Hydrogen Trade to Meet the 1.5°C Climate Goal," IRENA, July 2022, https://www.irena.org/publications/2022/Jul/Global-Hydrogen-Trade-Outlook.
[9] Arnout de Pee et al., "The clean hydrogen opportunity for hydrocarbon-rich countries," McKinsey, November 23, 2022, https://www.mckinsey.com/industries/oil-and-gas/our-insights/the-clean-hydrogen-opportunity-for-hydrocarbon-rich-countries.
[10] de Pee et al., "The clean hydrogen opportunity for hydrocarbon-rich countries."
[11] Yukichi Takaoka, Kentarou Mizumukai, and Yuichi Kameno, "Suiso Frontier, the First LH2 Carrier — Demonstration of Technologies and Operational Phase," June 2023, https://onepetro.org/ISOPEIOPEC/proceedings-abstract/ISOPE23/All-ISOPE23/ISOPE-I-23-490/524383.

primary inputs in several hard-to-abate industries such as fertilizers, refineries, and steel production.

Various hydrogen production methods and their associated greenhouse gas emissions are often classified by colors. The three most common production methods are grey, blue, and green hydrogen (Table 1). Grey hydrogen is hydrogen generated through natural gas, primarily through a process in which natural gas reacts with steam in the presence of a catalyst to produce hydrogen. Carbon dioxide is emitted as a byproduct of this process. The blue hydrogen synthesis process mirrors grey hydrogen, except for the addition of carbon capture technology, which captures a percentage of the CO2 byproduct, reducing overall emissions. Green hydrogen is defined as hydrogen produced using purely renewable energy resources (like wind, solar, hydropower). Specifically, renewable energy powers an electrolyzer, where electricity splits a water molecule into its constituent hydrogen and oxygen molecules. This process is emissions-free so long as the input electricity is also emissions-free. Note that some countries, like India, also consider biomass-derived hydrogen to be in the "green" class.

This report focuses on this production step of this value chain, specifically quantifying and comparing India's green hydrogen production costs with the cost of other methods of hydrogen production.

Table 1: Hydrogen Colors Emissions Intensity and Price in India

	EMISSIONS INTENSITY (kg CO2 eq/kg H2)	PRICE ($/kg)
BLUE HYDROGEN	5 – 8	$2.70 – $3.40
GREEN HYDROGEN	0	$5.30 – $6.70
GREY HYDROGEN	10 – 14	$1.90 – $2.40

Source: Author's analysis, with information from "Hydrogen offtake is tiny but growing," BNEF, November 14, 2023, https://about.bnef.com/blog/hydrogen-offtake-is-tiny-but-growing/#:~:text=Many%20companies%20have%20plans%20to,for%20clean%20hydrogen%20and%20derivatives.

Many of the world's largest economies look at green hydrogen as both a decarbonization tool and an economic opportunity. Many countries, in anticipation of a global green hydrogen trade market, have published their own national hydrogen strategies. Most strategies look to utilize green hydrogen for domestic decarbonization, domestic manufacturing growth, industrial job creation, and as a source of revenue through exports.

These goals create an interesting dynamic where most countries look to become hydrogen exporters. Only Japan, Germany, and the United Kingdom discuss the need for green hydrogen imports to meet decarbonization goals. Although France, South Korea, and Mexico have not explicitly stated their import/export intentions, the remaining G20 nations have distinctly outlined the export of green hydrogen as a key objective. With expected hydrogen exporters outnumbering expected hydrogen importers, the global hydrogen market will likely be competitive.

This push towards domestic decarbonization and a robust export market is underpinned by the ambitious production goals set by nearly all G20 countries, with most looking to multiply their current green hydrogen production capacity by over one hundred times by 2050. For instance, Argentina looks to produce over 5 million tons/year of green hydrogen by 2050, requiring a least 30 GW of electrolysis capacity. It currently has 0.8 megawatts (MW) of installed electrolysis capacity. This is not an isolated trend, with every G20 country (except for Mexico) looking to produce over 1 million tons/year of green hydrogen by 2050. Achieving these goals and staying in line with a 2050 net-zero emissions scenario will require significant increases in global electrolyzer production and additional renewable energy generation, on the order of a factor of eighty by 2030.

Table 2: The Current G20 Hydrogen Landscape

COUNTRY	H2 STRATEGY/ROADMAP	NUMBER OF PROJECTS	TOTAL INSTALLED ELECTROLYZER CAPACITY (MW)	EXPORT/ IMPORT FOCUS IN H2 STRATEGY
ARGENTINA	**Focus:** Increase in domestic manufacturing, export markets, generation of jobs. **Goal:** Produce 5 million tons/year of green hydrogen by 2050, 80% of which will be exported.	Feasibility study (3), Concept (4), Operational (1)	0.828	Export
AUSTRALIA	**Focus:** Hydrogen as next large energy export, domestic decarbonization in transport, gas networks, etc. **Goal:** Upwards of 300 billion AUD in investment opportunity, major global player by 2030.	Feasibility study (65), Concept (47), FID/ Construction (19), Operational (9), DEMO (6), Other/ Unknown (1)	3.67	Export
BRAZIL	**Focus:** Creation of export opportunities, domestic decarbonization, manufacturing and job growth. **Goal:** Install low carbon hydrogen plants by 2025, most competitive producer/exporter by 2030, consolidate hydrogen hubs by 2035.	Feasibility study (7), Concept (12), Operational (2), DEMO (2), FID/ Construction (1)	3.9	Export
CANADA	**Focus:** Encourage early deployment in mature applications. Incentivize production and demand via Clean Fuel Standard. **Goal:** Generate over 350,000 jobs, hydrogen to deliver 30% of Canada's total end-use energy by 2050.	Feasibility study (15), Concept (11), Operational (10), FID/ Construction (10), DEMO (5)	23.7	Export

CHINA	**Focus:** Domestic decarbonization in transport, electricity generation/ storage, etc. **Goal:** Produce 100,000 – 200,000 metric tons/year by 2025, 50,000 hydrogen vehicles by 2050.	Operational (21), Concept (15), Feasibility study (8), FID/ Construction (31), DEMO (5), Decommissioned (1) Decommissioned (1)	581.29	N/A
FRANCE	**Focus:** Decarbonize industry, hydrogen mobility, research/ innovation. **Goal:** Produce 700,000 tons/year and target price of $1.6/kg by 2030.	Operational (17), Concept (35), Feasibility study (40), FID/ Construction (19), DEMO (14)	19.9	N/A
GERMANY	**Focus:** Domestic decarbonization in heavy industry and transport sectors, building hydrogen transport networks. **Goal:** Decarbonize heavy industry and long-distance transport by 2030, 1,800 km of new/converted hydrogen pipelines by 2027-28.	Operational (54), Concept (31), Feasibility study (53), Demo (33), FID/Construction (25)	82.8	Import
INDIA	**Focus:** Become leading exporter of green hydrogen, domestic decarbonization, development of domestic manufacturing. **Goal:** Produce 5 million tons/ year and 125 GW of additional renewable energy capacity by 2030.	Concept (22), Demo (3), FID/ Construction (9),	13.36	Export
INDONESIA	**Focus:** Initial use for transportation sector by 2031, high temperature industrial heating processes by 2041, build export market **Goal:** Net zero emissions by 2060.	Concept (3), Feasibility study (3)	N/A	Export
ITALY	**Focus:** Decarbonize, heavy industry, long distance transport, refineries, and gas grid. **Goal:** 2% hydrogen penetration in final energy demand by 2030, 20% by 2050.	Operational (1), Concept (2), Feasibility study (2), DEMO (1)	3.95	Export
JAPAN	**Focus:** Decarbonize heating, transport, and production of e-fuel/e-methane. Explicit focus on safety. **Goal:** Consume 3 million tons per year by 2030, 20 million by 2050, and 12 million tons of ammonia per year by 2040.	Operational (6), Concept (11), Feasibility study (17), FID/ Construction (5), DEMO (3), Other/ Unknown (1)	18.91	Import
MEXICO	**N/A**	Concept (2), Feasibility study (2)	N/A	N/A

RUSSIA	**Focus:** Export to Europe and Asia. **Goal:** Export 200,000 tons by 2024, 2 – 12 million tons by 2035, and 15 – 50 million tons by 2050.	Operational (4), Concept (4), Feasibility study (7), FID/ Construction (2)	1	Export
SAUDI ARABIA	**Focus:** Global hydrogen supplier, diversify away from crude oil. **Goal:** Produce 2.9 million tons per year by 2030, 4 million tons per year before 2035.	Operational (4), Concept (4), Feasibility study (7), FID/ Construction (2)	N/A	Export
SOUTH AFRICA	**Focus:** Decarbonize economy, create economic opportunity domestically and through exports. **Goal:** Produce 500,000 tons per year by 2030, deploy 10 GW of electrolyzer capacity by 2030, and 15 GW by 2040.	Operational (2), Concept (6), Feasibility study (10), FID/ Construction (1)	3.5	Export
SOUTH KOREA	**Focus:** Decarbonizing transport through hydrogen cars and buses, utilize fuel cells for power generation. **Goal:** Produce 30,000 hydrogen-powered vehicles by 2030, build 70 liquid hydrogen refueling stations, and compose 7.1% of total energy mix with clean hydrogen.	Operational (6), Concept (9), Feasibility study (11), FID/ Construction (6), DEMO (2)	4	N/A
TURKEY	**Focus:** Domestic decarbonization in hard-to-abate sectors, blending into gas grid, export surplus. **Goal:** Reduce the levelized cost of hydrogen to $2.4 by 2035 and $1.2 by 2050, 5-20% hydrogen blend until 2025, then 20 – 100% between 2025 and 2040.	Operational (1), Concept (3), Feasibility study (2), FID/ Construction (1)	0.275	Export
UNITED KINGDOM	**Focus:** Domestic decarbonization, create jobs and economic growth. **Goal:** 10 GW of low carbon hydrogen production by 2030.	Operational (15), Concept (26), Feasibility study (36), FID/ Construction (12), DEMO (4), Other/ Unknown (1)	10.39	Import
UNITED STATES	**Focus:** Domestic decarbonization in "high-impact end uses," reduce cost of green hydrogen, focus on regional networks. **Goal:** Produce 10 million tons/ year of clean hydrogen by 2030, establish green hydrogen costs of $2/kg by 2026 and $1/kg by 2031, deploy regional clean hydrogen hubs	Operational (27), Concept (38), Feasibility study (55), FID/ Construction (27), DEMO (9), Other/ Unknown (2)	52.95	Export

Source: Data sources for each country entry can be found in Appendix B. Note that this table does not include the European Union or African Union.

3. INDIA'S HYDROGEN GOALS

India recently launched its National Green Hydrogen Mission, aiming to become a leader in the global green hydrogen market. The Green Hydrogen Mission primarily positions India as a global green hydrogen exporter, designating 70 percent of its 2030 green hydrogen production targets (around 3.5 million tons) for export and the remaining hydrogen for domestic decarbonization. The mission includes reductions in taxes and tariffs along with financial incentives totaling nearly $2 billion to increase domestic electrolyzer manufacturing and green hydrogen production.[12]

Table 3: Assumptions and Parameters to Estimate Cost

PARAMETER	VALUE
Cost of Capital (Discount Rate)[13]	5.9% -> 15%
Electrolyzer Efficiency (kWh/kg)[14]	50
Solar Costs (for India, $/kW)[15]	Capital/Equipment Costs: 590 Operating Costs: 9.6
Electrolyzer Costs (Low, Medium, High Scenarios 2022 $/kW)[16]	Capital/Equipment Costs:1150, 1450, 1800 Operating Costs: 17, 21, 26
Lifetime (years)[17]	20

Source: Methodology and full input parameters can be found in Appendix A and Appendix C.

This study computes green hydrogen production costs at locations across India. Cost estimates use inputs unique to each location at a geographical resolution of 0.25 degrees latitude by 0.25 degrees longitude (approximately 550 km^2). At each grid cell, these inputs include parameters such as renewable energy generation from wind and solar patterns based on hourly values averaged over 15 years, capital and operating costs, cost of capital, and plant lifetime. Then the assessment finds the lowest cost of hydrogen and the optimal ratio between renewable energy generation and electrolyzer capacity to generate green hydrogen.

For India, only solar generation due to greater accessibility throughout the region is considered.[18] Grid-connected electrolyzers are not considered to be sources of green hydrogen, as in order to ensure that embodied grid emissions (grid electricity gener-

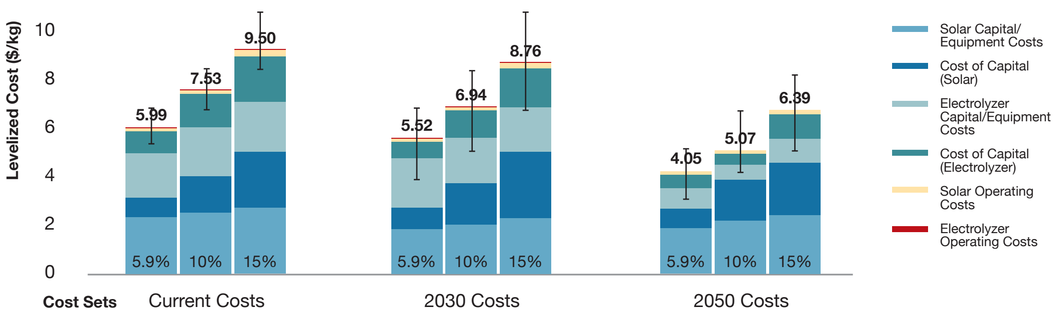
[12] "Nearly 50 MMT per annum of CO2 emissions can be averted through production and use of Green Hydrogen as targeted under National Green Hydrogen Mission: New & Renewable Energy Minister," PIB Delhi, August 1, 2023, https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1944758.
[13] IRENA, "Data Appendix: Country and technology-specific real after-tax WACC assumptions for 2021," accessed on November 17, 2023, https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/May/IRENA_Cost_of_financing_renewable_power_Appendix_2023.pdf?rev=0c9288a22ab44676a1fd5b8ca0c774e8.
[14] Gunther Glenk, Philip Holler, and Stefan Reichelstein, "Advances in Power-to-Gas Technologies: Cost and Conversion Efficiency," MIT CEEPR, April 2023, https://ceepr.mit.edu/wp-content/uploads/2023/04/MIT-CEEPR-WP-2023-09.pdf.
[15] Michael Taylor et al., "Renewable power generation costs in 2021," IRENA, July 2022, https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021.
[16] Herib Blanco et al., "The Future of Hydrogen," IEA, June 2019, https://www.iea.org/reports/the-future-of-hydrogen.
[17] Muhammad Arfan et al., "Life Cycle Assessment and life cycle costing of hydrogen production from biowaste and biomass in Sweden," Energy Conversion Management, September 2023, https://doi.org/10.1016/j.enconman.2023.117262.
[18] The World Bank, "Global Solar Atlas," accessed on December 5, 2023, https://globalsolaratlas.info/.

ated from coal or gas) are accounted for, strict regulations must be put in place, like the regulations instituted by the United States in from the Inflation Reduction Act.[6] [19] Depending on an electricity grid's generation profile, a direct grid-electrolyzer system could result in more emissions than grey and blue hydrogen generation.[20]

Furthermore, the author chose to analyze the median instead of the minimum cost of production to represent overall production costs more accurately throughout the region. Importantly, this analysis does not consider the effect of any domestic subsidies or tax incentives currently in place. Costs presented are purely production and not landed costs. It should be noted that these costs are likely underestimates of true production costs as parameters such as the cost of water, land permitting, and construction time are not considered. Also note that all costs presented are levelized cost, computed by taking the total capital and operating costs divided by the total amount of hydrogen produced, both discounted over the lifetime of the hydrogen generation plant. Additional costs accrued through compression, storage, and transportation would likely increase the levelized cost.[21]

4. CAPITAL AND ITS COST ARE THE LARGEST DRIVERS OF SOLAR-POWERED GREEN HYDROGEN PRODUCTION COSTS IN INDIA

Figure 2: Median Green Hydrogen Production Cost Sets



This is a breakdown of median green hydrogen production costs throughout India at various discount rates. Each bar shows the median production cost at different costs of capital (5.9 percent, 10 percent, 15 percent). Error bars represent levelized cost given higher and lower electrolyzer cost estimates. Solar and electrolyzer capital expenditures make up most costs. As electrolyzer costs fall, its proportion of total levelized cost falls accordingly.

Source: Author's analysis.

Production costs are estimated under three different electrolyzer cost scenarios: neutral/business-as-usual, an optimistic scenario with lower electrolyzer cost assumptions, and a pessimistic scenario with higher electrolyzer cost assumptions across various costs of capital (Figure 2). Costs are projected in three different years: 2022, 2030 and 2050. In 2022, under the lowest assumptions for cost of capital, estimated median green hydrogen costs in India are approximately $6 per kilogram ($5.30-6.70 per kg). By 2030, estimated costs fall to $5.50 ($4.30-6.70 per kg). By 2050, costs fall to $4.05 ($3.30-4.80 per kg). These cost

[19] "Section 45V Credit for Production of Clean Hydrogen; Section 48(a)(15) Election To Treat Clean Hydrogen Production Facilities as Energy Property," IRS, December 26, 2023, https://www.federalregister.gov/documents/2023/12/26/2023-28359/section-45v-credit-for-production-of-clean-hydrogen-section-48a15-election-to-treat-clean-hydrogen.

[20] Wilson Ricks, Qingyu Xu, and Jesse D Jenkins, "Minimizing emissions from grid-based hydrogen production in the United States," IOP Science, January 2023, https://iopscience.iop.org/article/10.1088/1748-9326/acacb5.

[21] "Hydrogen Market Report," FIPI, October 23, 2023, https://www.fipi.org.in/assets/pdf/downstream-report/Hydrogen%20Market%20Report.pdf.

ranges align with estimates seen in a number of previous analyses.[22] The main assumptions to derive these figures are outlined in Table 3 with a full description in Appendix A.

The largest drivers of production cost are cost of capital and capital equipment cost of solar energy systems and electrolyzers. In 2022, the analysis suggests that solar and electrolyzer capital costs account for approximately two-thirds of overall levelized cost, evenly split between equipment costs and the cost of capital (discount rate). Operating costs of solar systems and electrolyzers for green hydrogen production are less than 5 percent of total levelized costs.

Even with optimistic reductions in capital equipment costs, the cost of capital required to finance that equipment must also decrease. Alone, falling capital costs result in cost estimates of $4 per kg by 2050, two times more expensive than 2022 conventionally produced grey hydrogen costs (Table 1). Higher costs of capital (10 percent and 15 percent) increase this disparity, resulting in production cost estimates 20-60 percent higher than the lowest cost of capital (5.9 percent), creating a cost premium between 2 – 3.5 times current grey hydrogen prices.

Cost of capital is consequently a limiting factor in green hydrogen production costs. Cost of capital for green hydrogen projects can vary widely, often because of diverse risk factors.[23] These include:

<u>Technology Risk:</u> Green hydrogen production is a new and growing industry. Electrolyzer costs are uncertain, safety standards and definitions range from country to country, or are non-existent. The lack of large-scale projects means that uncertainty also exists regarding maintenance time, electrolyzer efficiencies and lifetimes, repair costs, and other unforeseen challenges. These challenges increase the technology risk associated with project financing, resulting in significantly higher costs of capital and subsequent production costs.

<u>Demand Risk:</u> Securing both long and short-term off-takers for hydrogen production is one of the largest barriers for projects looking for funding.[24] Without an established selling price, hydrogen production is subject to market volatility and the uncertainties of fluctuating demand trends.

<u>Policy Risk:</u> Policy incentives, governmental regulations, and clean hydrogen standards are evolving. The absence or presence of these incentives and regulations can swing the price difference between grey and green hydrogen significantly, resulting in added uncertainty for investors or project developers.

The presence of these risk components can result in costs of capital upwards of 20 percent higher than the assumed cost of capital here.[25]

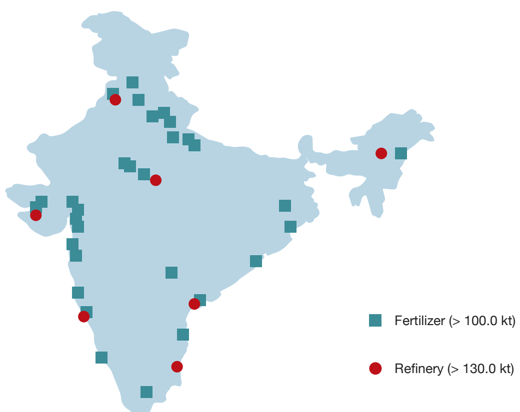
[22] Tirtha Biswas, Deepak Yadav, and Ashish Guhan Baskar, "A Green Hydrogen Economy for India," CEEW, December 2020, https://www.ceew.in/sites/default/files/CEEW-A-Green-Hydrogen-Economy-for-India-14Dec20.pdf.
[23] Moongyung Lee and Deger Saygin, "Financing cost impacts on cost competitiveness of green hydrogen in emerging and developing economies," OECD, November 2023, https://one.oecd.org/document/ENV/WKP(2023).
[24] Lee, "Financing cost impacts on cost competitiveness of green hydrogen in emerging and developing economies."
[25] Lee, "Financing cost impacts on cost competitiveness of green hydrogen in emerging and developing economies."

5. DECARBONIZING REFINERIES AND FERTILIZERS BY TRANSITIONING TO GREEN HYDROGEN

India could partly address demand risk by focusing its green hydrogen efforts on two sectors with tangible, established hydrogen demand: fertilizers and petroleum refining, where the country ranks globally, third and fourth, respectively.[26 27 28 29]

These industries, which currently use approximately 6 million tons of grey hydrogen, represent an implicit demand baseline, making it easier for producers to secure off-take agreements and hedge project risk.[30] However, this transition from grey to green hydrogen will incur a steep cost premium.

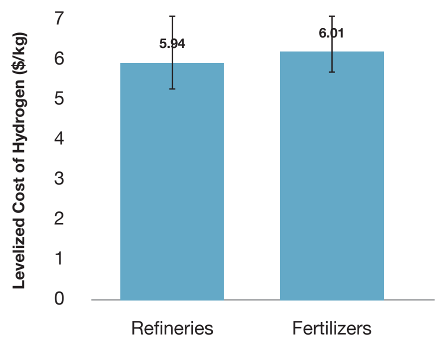
Figure 3: Fertilizer plants and Refineries in India



Fertilizer plants (squares) and refineries (circles) in India with hydrogen production capacities.

Source: Author's analysis.

Figure 4: Levelized Cost Comparison



Median levelized hydrogen costs of fertilizer and refinery plants across India. Error bars show minimum and maximum values. The cost of capital is set to 5.9 percent.

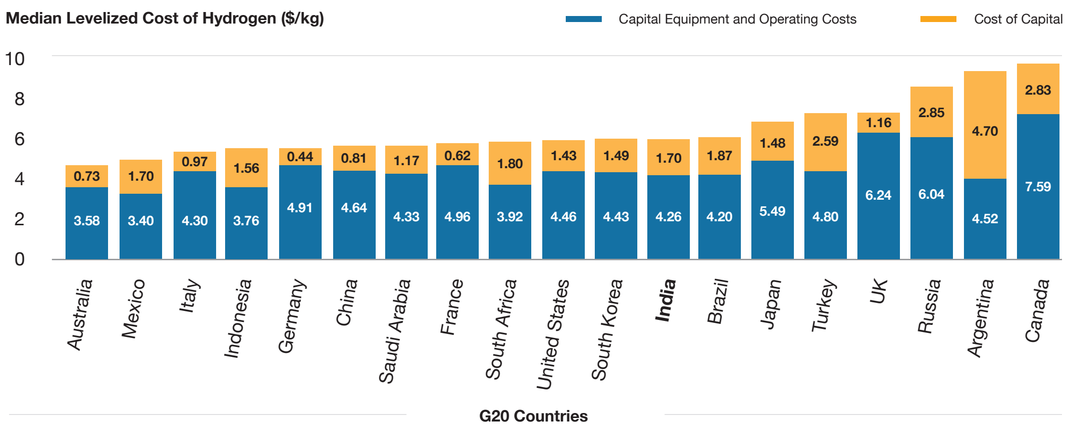
Source: Author's analysis.

Currently, fertilizer plants and refineries sit throughout India with estimated green hydrogen production costs ranging between $5.50 and $7.30 per kg (see Figures 5 and 6).[31 32] Compared to grey hydrogen, the cost of green hydrogen production using solar energy at locations of fertilizer plants and refineries is three- to four-fold higher. These costs do not consider the expenses involved in retrofitting existing plant designs or generating new workflows to integrate green hydrogen generation systems. Moreover, production at coastal plants can likely achieve reduced costs by utilizing wind in conjunction with solar generation.

[26] "Production volume of nitrogen fertilizer worldwide in 2018, by country," Statista, April 2021, https://www.statista.com/statistics/1252656/nitrogen-fertilizer-production-by-country.
[27] "Crude oil refinery capacity worldwide in 2010 and 2022, by major country," Statista, June 2023, https://www.statista.com/statistics/273579/countries-with-the-largest-oil-refinery-capacity/.
[28] Friedrich et al., "This Interactive Chart Shows Changes in the World's Top 10 Emitters," WRI, March 2023, https://www.wri.org/insights/interactive-chart-shows-changes-worlds-top-10-emitters.
[29] "Renewable Energy Sector," InvestIndia, February 23, 2024, https://www.investindia.gov.in/sector/renewable-energy.
[30] Gül et al., "Global Hydrogen Review 2023."
[31] "Annual Report 2020-2021," Department of Fertilizers, 2021, https://www.fert.nic.in/sites/default/files/2020-082022-08/Annual%20report%20of%20Department%20of%20Fertilizer%202020-2021.pdf.
[32] Hall et al., "The Potential Role of Hydrogen in India," 2020, https://www.teriin.org/sites/default/files/2021-07/Report_on_The_Potential_Role_of_%20Hydrogen_in_India.pdf.

6. ABSENT INCENTIVES INDIA'S GREEN HYDROGEN PRODUCTION COSTS ARE HIGHER THAN MANY G20 COUNTRIES

Figure 5: Comparison of G20 Median Levelized Costs of Production Using Solar Renewable Energy Resources



India ranks as the 12th cheapest median production cost. Total costs are split into two components, cost of capital and capital equipment/operating cost. Cost of capital in countries with a lack of solar resources has increased price impact as countries must overbuild solar systems to compensate for the lack of resources.

Source: Author analysis. See Appendixes A, B, and C.

Comparing India's green hydrogen production costs with the rest of the G20 underscores the importance of the cost of capital. Estimated costs in Figure 7 include two components: capital and operating costs and the cost of capital. While capital and operating costs to produce green hydrogen may be lower in some countries like India, many of these countries incur a higher cost of capital, increasing their overall cost of green hydrogen production.

Currently, India stands 12th in the G20 in terms of median green hydrogen production cost, at approximately $6 per kg. This cost is 40 percent higher than the G20's least expensive producer, Australia. Crucially, India's production costs are higher than several countries positioning themselves hydrogen importers like Germany, due to a low cost of capital, and countries positing themselves exporters like Saudi Arabia, South Africa, and Australia. Factors such as access to lower discount rates (notable in Germany and France) and better median solar resources (seen in Australia, Saudi Arabia, and China) drive these cost differences. It is important to note that this analysis is based solely on solar energy. Countries like Argentina, Canada, Russia, and France, which have greater access to wind resources, could significantly reduce production costs by utilizing wind energy.

These cost differences pose challenges for India's hydrogen exporter goal. Several importers and exporters within the G20 have lower production costs, meaning that competing in an international hydrogen market will require significant efforts to achieve cost competitiveness. To be a competitive exporter within the G20, India must reduce median production costs by about 30 percent. To be able to produce hydrogen at a cost cheaper than G20 importers (Germany), median production costs must be reduced by around 10 percent. While India has several tax subsidies and financial incentives in place through the Green Hydrogen Mission, several other G20 countries have done the same. The United States has released its 45V hydrogen tax credit, offering up to $3.00 per kilogram of green hydrogen produced, Argentina is providing a complete tax break for green hydrogen produced within the next decade, and Australia is providing over $1 billion dollars in subsidies.[33][34] For India to be cost competitive, its financial incentives and policy mechanisms must not only match these international efforts but exceed them in order to bridge current cost disparity.

6. CONCLUSION AND RECOMMENDATIONS

India's role within the growing global green hydrogen value chain is uncertain. Estimated production costs of off-grid solar-based green hydrogen in India are higher than conventional hydrogen production methods and higher than in other countries. This poses challenges for domestic substitution and international export. Falling electrolyzer costs are not enough to make up this difference. Even in the case where blue and grey hydrogen prices stay constant, assumed capital and operation costs reductions by 2050 still result in green hydrogen being 20 percent and 70 percent more expensive than its blue and grey counterparts, respectively. Under current cost conditions, replacing a kilogram of grey hydrogen with a kilogram of green hydrogen would require a cost reduction of $3.30 per kilogram in India. If India were to directly subsidize this cost difference and meet its goal of 5 million tons of green hydrogen by 2030, it would require $16.5 billion per year, significantly more than the current $2.4 billion outlay. Importantly, a majority of these incentives are not slated for direct subsidies and are instead meant to encourage research and development primarily to reduce electrolyzer capital costs. However, our analysis shows that even with all-in electrolyzer costs of $200/kilowatt (kW), levelized costs are approximately 70 percent higher than current grey hydrogen prices. Thus, to achieve cost parity, these incentives must also reduce other cost drivers, such as the cost of capital, or make grey hydrogen more expensive through a price on carbon emissions.

India may be able to reduce its cost of capital by refocusing its policy and financial mechanisms towards incentivizing domestic decarbonization efforts for two major reasons: guaranteed off-takers and reduced uncertainty. By looking to replace grey hydrogen production in refineries and fertilizer plants (many of which are owned by state-owned enterprises), India can build out and de-risk projects while not having to secure outside demand. With only 10 percent of the clean hydrogen capacity planned by 2030 having an off-taker, India's domestic demand acts as a clear advantage.[35] Thus, to capitalize on this while simultaneously reaching its decarbonization goals, India could look to focus capital away from a high-risk, competitive, and uncertain export market and instead shift towards decarbonizing its refineries and fertilizer plants. Such a shift could shed uncertainty shrouding hydrogen production, possibly resulting in lower costs of capital which can have significant effects on overall levelized production costs.

The effectiveness that guaranteed demand and off-take offers has been seen before,

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[33] "Section 45V Credit for Production of Clean Hydrogen; Section 48(a)(15) Election To Treat Clean Hydrogen Production Facilities as Energy Property," IRS.

[34] Charles Newbery, "Argentina to submit bill providing incentives to produce hydrogen for export," S&P Global, May 19, 2023, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/051923-argentina-to-submit-bill-providing-incentives-to-produce-hydrogen-for-export#:~:text=The%20bill%20calls%20for%20providing,a%20draft%20of%20the%20bill.

[35] "Hydrogen offtake is tiny but growing," BNEF, November 14, 2023, https://about.bnef.com/blog/hydrogen-offtake-is-tiny-but-growing/#:~:text=Many%20companies%20have%20plans%20to,for%20clean%20hydrogen%20and%20derivatives.

specifically with South Africa's Renewable Energy Independent Power Producer Procurement Program. By introducing a tender process for renewable energy companies that, when selected, ensured a 20-year purchase price allocation (PPA) with Eskom, South Africa's state utility, the country was able to incentivize renewable energy generation at reduced risk.[36] Since 2011, the program has created 64 new renewable energy independent power producers (IPPs) and $14 billion in investment to fund the creation of 3,922 MW of various renewable energy capacity.[37] India is taking an analogous approach to de-risking hydrogen investment and development by investigating to see the potential for a green hydrogen mandate in fertilizer and refineries.[38]

Access to lower costs of capital will also accelerate India's pursuit to become a leading global hydrogen exporter. Cost comparisons show that Indian green hydrogen while potentially cost competitive against other G20 countries due to abundant solar resources, pays a penalty for higher cost of capital. This makes economic viability within the global export market without financial incentives difficult. If green hydrogen projects in India pay lower costs of capital, they can begin to make up the cost difference between India and the rest of the G20. While a focus on domestic production and decarbonization would likely decrease risk, other financial incentives such as concessional capital could have similar effects.

Appendix A: Plant and Financial Input Parameters

This model accounts for electrolyzer degradation and stack replacement costs across the lifetime of the hydrogen plant. The number of stack replacements and the overall cost associated with each replacement is aggregated into the overall electrolyzer CAPEX. The source of data for each parameter can be found in Appendix C. This analysis contains limitations and uncertainty. All cost estimates described are purely production costs and do not include the cost of storage or transport. Land accessibility is not addressed and would likely increase estimated production costs. Renewable energy generation and electrolyzers are assumed to be co-located, thus transmission costs are not considered. Due to the lack of reliable electrolyzer operational costs at different years and in different scenarios, operational expenditure costs in future years and scenarios are scaled from current (2022) costs by the percentage increase or decrease in capital costs. Significant uncertainty exists within true electrolyzer cost and project discount rate estimates due to the lack of developed, large-scale green hydrogen projects. Furthermore, the inclusion of wind or a combination of solar and battery storage as renewable energy resources would provide increased capacity factors and thus, lower production costs. Finally, true production costs estimates will require an analysis of compression, storage, and transport costs. Further work of this analysis may include wind solar hybrid locations.

PARAMETER	VALUE	SOURCE
India Cost of Capital (Discount Rate)	5.9% -> 15%	IRENA (2022)
Electrolyzer Efficiency (kWh/kg)	50	CEEPR (2023)
Solar Costs (for India, $/kW)	Capital/Equipment Costs: 590 Operating Costs: 9.6	IRENA (2021)
Electrolyzer Capital Costs (Low, Medium, High Scenarios 2022 $/kW)	1100, 1450, 1800	IEA (2019)
Electrolyzer Operating Costs (Low, Medium, High Scenarios 2022 $/kW)	17, 22, 28	IEA (2023)
Electrolyzer Operating/Capital Costs (Low, Medium, High Scenarios 2030 $/kW)	Capital: 650, 1225,1800 Operating: 10, 18, 28	IEA (2019)
Electrolyzer Operating/Capital Costs (Low, Medium, High Scenarios 2050 $/kW)	Capital: 200, 550, 900 Operating: 3, 9, 14	IEA (2019)
Lifetime (years)	20	Arfan et al. (2023)
G20 Cost of Capital (Discount Rate)	Varies	IRENA (2022)
Global Solar Costs	Varies	IRENA (2021)
Renewable Energy Data (Solar Irradiance)	Varies	ERA 5 Reanalysis (2007 – 2022)

Electrolyzer Stack Degradation Rate (% per year)	2	Energy Proceedings (2022)
Allowed Electrolyzer Degradation Before Replacement (%)	70	
Electrolyzer Replacement Cost (% of Initial CAPEX)	30	

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